Progress in Laser Propagation in a Maritime Environment at the Naval Research Laboratory

G. C. Gilbreath[1], W. S. Rabinovich[1], C. I. Moore[1], H. R. Burris[2], R. Mahon[3],
K. J. Grant[4], P. G. Goetz[1], J. L. Murphy[1], M. R. Suite[1], M. F. Stell[2], M.L. Swingen[1],
L. M. Wasiczko[1], S. R. Restaino[1], Christopher Wilcox[1], J. R. Andrews[1], and W. J. Scharpf[1]
Charmaine.gilbreath@nrl.navy.mil

ABSTRACT

In this paper, we summarize progress in free space laser propagation research at the U.S. Naval Research Laboratory, specifically in the context of propagating and detecting signals through the atmosphere in a maritime environment. Transmission through the atmosphere over large bodies of water presents different challenges than transmission through the atmosphere over land. Our paper reports some of these findings as well as progress in our collaborative efforts to mitigate turbulence to enhance our data links.

Key Words: Free space optical communications, atmospheric propagation, retromodulators, modulating retroreflector, maritime propagation

1. INTRODUCTION

The Naval Research Laboratory (NRL) investigations into free space optical communications (FSO) span a number of areas which are tied to the types of links of specific interest to Navy needs. These areas are defined essentially by data rate. Links requiring data rates of 100 Mbps to tens of Gigabits (Gbps) are explored using conventional, or direct, architectures requiring gimbaled laser transmitters and telescope-based receivers at each end of the link. Links from kbps to 100 Mbps are investigated using asymmetric architectures where one end of the link uses one or more modulating retroreflectors (MRR) as the communications terminal and the onus of the link is with the interrogator remotely located with respect to the sensor and the MRR units. The MRRs themselves fall into two classes: corner-cube units (CCMRR) which can support up to 10 Mbps with current devices and cats-eye units (CEMRR) which we anticipate will support up to 100 Mbps. To support this work, NRL has efforts in the conception and development of relevant technologies, such as laser amplifiers and high data rate modulators, in multiple quantum well (MQW) modulators, and in advanced telescope concepts. We also design, develop and test advanced techniques in coding and system architectures which are required in order to successfully transmit data reliably through the atmosphere. We are very interested in the propagation effects which characterize over-the-water conditions and land-water boundaries. In this paper, we report an overview of progress in our work as well as that of our collaborators.

2. OPERATIONAL CHALLENGE

The operational challenge that we address in our research is how to transfer large quantities of data, quickly, at low "wall plug" power draws, with high fidelity, and in such a way that the recipient of the data is not put at risk. The focus of the work is to develop devices, architectures and techniques to support inter-platform infrared data links where the platforms include spacecraft-to-spacecraft architectures, unmanned vehicles-to-remotely located

---

[1] Author is with the U. S. Naval Research Laboratory, 4555 Overlook Ave., SW, Washington, D. C. 20375
[2] Author is with Research Support Instruments, Inc., 4325-B Forbes Blvd., Lanham, MD. 20706
[3] Author is with Jaycor/Titan, Inc., 1410 Spring Hill Rd., McLean, VA. 22102
[4] Author is with Defence Science & Technology Organisation, PO Box 1500, Edinburgh SA 5111 Australia

Free-Space Laser Communications V, edited by David G. Voelz, Jennifer C. Ricklin, Proc. of SPIE Vol. 5892
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.633390

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**
4. TITLE AND SUBTITLE **Progress in Laser Propagation in a Maritime Environment at the Naval Research Laboratory**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,4555 Overlook Avenue, SW,Washington,DC,20375**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**		**9**	

interrogators, or unattended ground sensors. Architectures include fixed point-to-point, mobile-to-fixed and mobile-to-mobile scenarios. To this end, we are investigating devices and architectures in the near-infrared regime.

We are specifically investigating propagation properties and device development at 1550 nm. This wavelength translates to a carrier than can ultimately bear tens of gigabits of modulation. The infrared carrier also offers an alternative to the crowded radio frequencies (RF) as there are no allocation or interference problems. For the specific applications of interest, the foot print at the target is small (λ/d is typically on the order of milliRadians which translates to a meter at a kilometer range, for example). In addition, the form factor of the communications terminals can be very small and the power draw commensurately low. Trades with RF equivalent are dependent on data rate and range.

Operation at 1.55 microns has three major advantages. First, a link can be made eye safe more readily in that potential eye damage will be corneal rather than retinal for an equivalent amount of power at the shorter wavelengths. Furthermore, kilometer-level links can be closed at intensities that are non-threatening to the human eye with over-the-counter components. Second, the atmosphere offers a window of transmission at 1.55 microns (see Section 6). Finally, there has been substantial investment from the telecommunications industry in components which are optimized at this frequency. Hence, we can leverage substantial investment from the private sector.

There are disadvantages. The infrared links are line-of-sight (LOS). Non-LOS links can be architected but require relays. Also, the wavelength is susceptible to some weather conditions (dense fog and cumulous clouds) as well as to obscuration and beam blockage.

3. ARCHITECTURES

At NRL, we are interested in two types of free space architectures. One is a direct link where there is a laser transmitter and receiver (Tx/Rx) on both sides of the link. This configuration can support very high bandwidths – tens of gigabits per second – at very long ranges – hundreds of kilometers. It is suited for ground-to-satellite communications as well as longer LOS terrestrial ranges. These types of links require gimbaled tracking and pointing on both sides of the links. At the lower data rates (100 Mbps and less), form factor, mass, and power draw can be equivalent to a Ka band terminal (1). The link itself is dominantly limited by a range-squared loss.

The NRL is also actively investigating devices and approaches that support asymmetric links. These types of links place a very small communications terminal at a remote location. The communications terminal may or may not be directly coupled to the sensor. The terminal itself is very small, requires an extremely low power draw, and can support data bandwidths on the order of kilobits to hundreds of Megabits per second. This type of link would support short to medium ranges (typically meters to tens of kilometers). If the data rate is relatively low (kilobits to a Mbps), a Leo-to-earth link could also be supported. Our approach is to use modulating retroreflectors (MRR) which have been describedelsewhere in the literature (2-3).

The onus of this type of link lies with the Transmit/Receive (Tx/Rx) unit. Essentially, a remotely located interrogation beam from the Tx/Rx interrogates the MRR. The MRR retroreflects modulated light which is in turn received and demodulated at the interrogator. The concept is illustrated in Figure 1. Loss can be mitigated by increasing the laser power, decreasing the divergence, maintaining good pointing, increasing the collection area, and using sensitive detectors with low noise amplifiers. However, the dominant loss for this type of architecture is the range-to-the-fourth dependence.

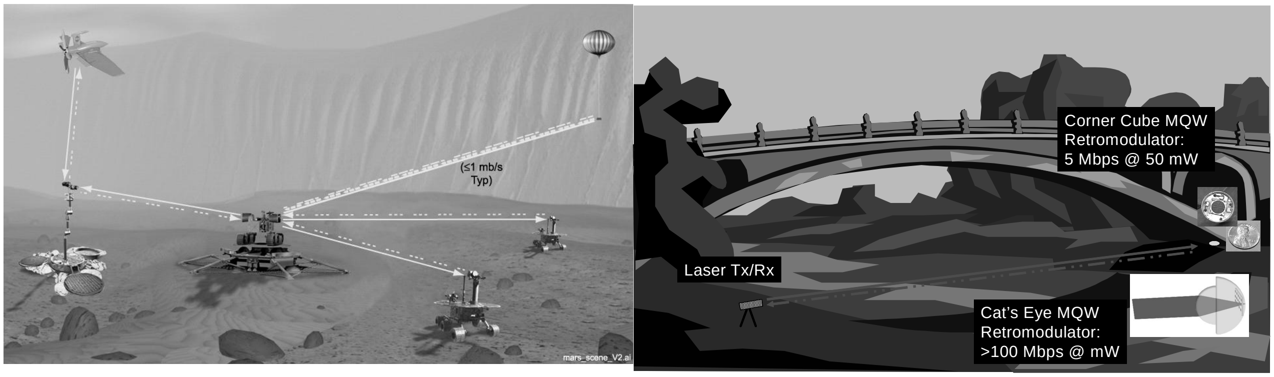


Figure 1. Asymmetric free space data links: (a) Lander-Probe application; (b) Remote data harvesting using a compact laser transmit/receive unit.

4. PROGRESS IN DEVICE DEVELOPMENT

At the core of the asymmetric program is NRL's Multiple Quantum Well (MQW) modulating retroreflectors. These devices enable fast data rate transfer with very small power draw (milliwatts) at very low mass (10 grams and less). Two architectures are under research and development. The first is based on a corner cube retroreflectors (CCMRR). Essentially, the MQW shutter is coupled with a standard corner cube retroreflectors to provide a transmissive device that serves as a shutter when a small amount of voltage is alternatively applied to the unit. Absorbance characteristics change with the application of the voltage and the device goes transparent or opaque alternatively (4). Present generation technology offers a device which can support realtime compressed color video at 30 frames per second, at 5 Mbps, using 50 mW of power and packaged is the size of a dime. When configured into an array, these units can be arranged to open up the field-of-regard (FOR). Figure 2 shows photos of the single device and of the array in present use. The latter is populated with units that offer a $(1/e)^2$ FOR of about 25 degrees and the array offers a 60 degree FOR.

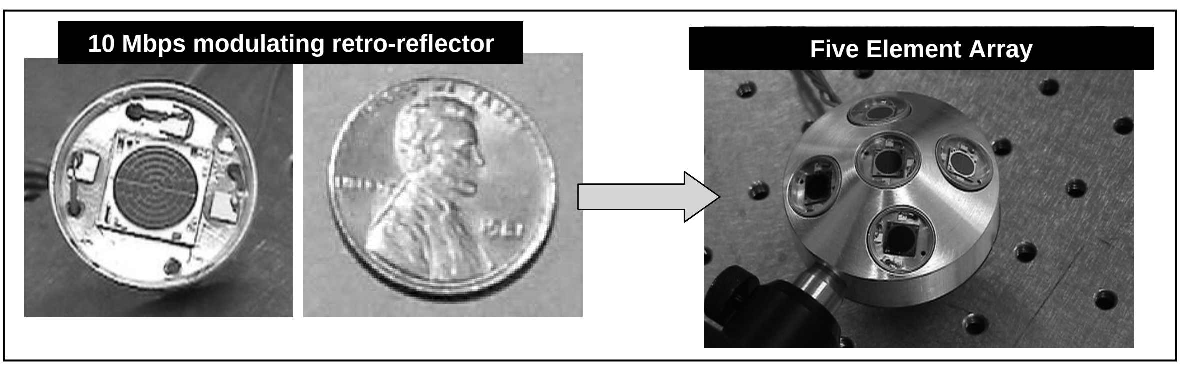


Figure 2. Corner-Cube modulating retroreflectors using Multiple Quantum Well shutters are shown. Units can be configured into arrays to increase fields-of-regard.

The second uses a cat's eye approach (CEMRR) (5). These devices couple essentially very small telescoping optics with an array of very small modulators. The array is placed at the focal plane and electronics detect and modulate only those modulators which are illuminated. Since the MQW devices are essentially resistance-capacitance (RC) devices whose speed is dependent on the area, the smaller units enable much faster modulation. We have reported

up to 70 Mbps in free space (6) and anticipate the development of devices which can support greater than 100 Mbps. Graphics and photographs illustrating this type of retromodulator are shown in Figure 3.

The CCMRR and CEMRR devices have been developed to be so efficient in their power draw that they have exposed the parasitic loading from other parts of a given sensor/MRR comms package. Most notably, digitization at the sensor, which has advantages in terms of coding to propagate with good Bit Error Rate (BER) through the atmosphere. may be more effectively traded to the Tx/Rx if the application requires minimum power at the sensor. To that end, we have begun to explore analog modulation techniques to determine optimum methods to save power. Specifically, we are exploring frequency modulation techniques. First results are reported elsewhere in this Proceedings (7). An audio signal was sent over a free space link on the laboratory bench and the signal was recovered with fidelity. The challenge will come when we propagate through the atmosphere which is the subject of future study.

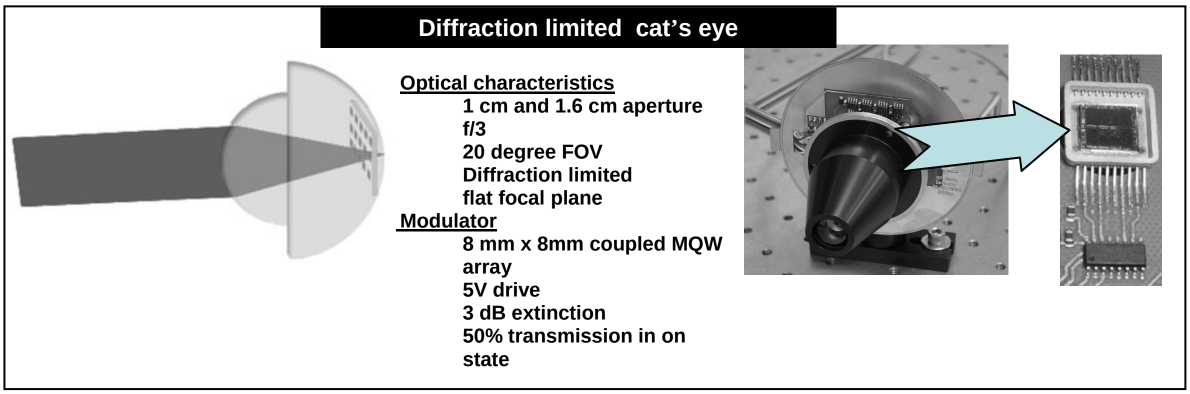


Figure 3. Cat's Eye Modulating Retroreflector developed at NRL. Unit supports 70 Mbps using milliwatts of power.

For low data rates (kilobits per second and lower), we are investigating photovoltaically-driven CCMRRs. Advancements in this area have lead to a recent design which was demonstrated to support 100 kHz using 100 microwatts of incident solar power on a monolithically integrated module (MIM) PV cell. (8). The implications for this device for tagging and ultra-low powered remotely located sensors is clear. Figure 4 is a photograph of this unit.

Further development is underway to make the MIMs devices responsive at 1550 nm. At a minimum, this would increase the efficiency of the MRR's power requirements. If the data rate is low, the MIMS-MRR device holds the promise of self-powered or nearly self-powered MRRs.

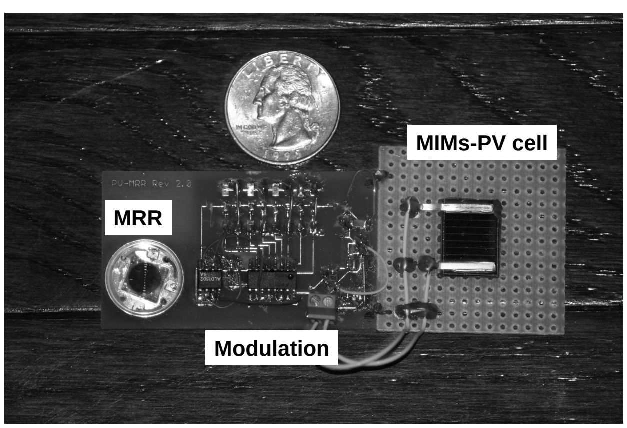


Figure 4. Photovolatically driven CCMRR is shown above. This unit supports 100 kHz with 100 microwatts of power generated from the sun by the MIMs device.

As we migrate to analog modulation at the MRR itself, characterization of the atmosphere and development of techniques to mitigate its effects are becoming more compelling to ensure viable links. Thus, NRL is also developing with low cost, compact adaptive optics systems (AO) based on deformable mirror technology (9). Recent work includes coupling MEMS-based deformable mirror with a tip/tilt stage in a compact mount to provide correction of several Zernike orders. This work will have real implications for low cost, readily implementable wavefront correction for FSO applications.). Figure 5 is a diagram of a test configuration used to characterize the device under development by Wilcox, et. al. (10).

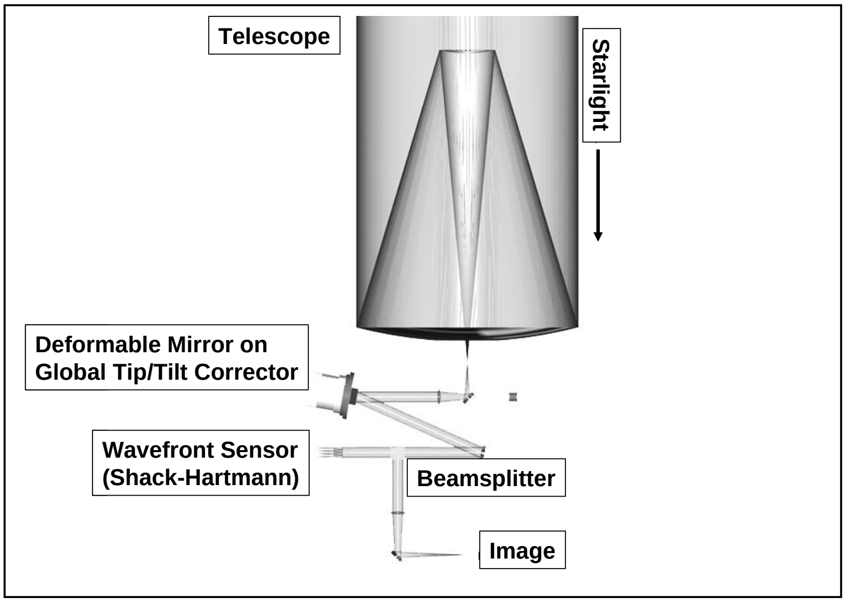


Figure 5. Test Configuration to characterize efficacy of deformable mirror on a Tip/Tilt stage for wavefront correction.

5. TESTBEDS

Testbeds have been developed both in the laboratories and in the environment to test devices and characterize systems in the atmosphere unique to the maritime environment. To investigate which wavefront sensor might be the most effective, an optical testbed has been developed for the comparative analysis of devices based on a modified Mach-Zehnder interferometer design. This system provides simultaneous measurements of the wavefront sensors on the same camera by using a common aberrator. The initial application for this testbed was to evaluate a Shack-Hartmann and Phase Diversity wavefront sensors referenced to the interferometer. In the current configuration of the testbed, aberrations are controlled using a liquid crystal spatial light modulator, and calibrated using a deformable mirror. This testbed has the added benefit of being able to train the deformable mirror against the spatial light modulator and evaluate its ability to compensate the spatial light modulator . This work is described in greater detail in this Proceedings (11).

As has been previously reported in the literature (12), the NRL has developed Free Space Optical (FSO) communications testbeds at the Chesapeake Bay Detachment (CBD) in Chesapeake Beach, MD. The facility enables on land and across-the-bay links. The west section of the testbed is located at CBD, and the east end is located at Tilghman Island (TI). Both locations are in Maryland and are separated by 16.2 km of water. Significant improvements have been made this past year in the facilities' resources which are described elsewhere in this Proceedings (13). Most notably are the new capabilities to enable long term monitoring of atmospheric conditions. Propagation effects over the water affect free space optical links quite differently from links over land and this data

will provide inputs to calibrate and tune models such as PAMELA and others. In addition, plans to explore efficient hybrid rf-to-optical transitions are underway to adapt to different weather conditions.

6. ATMOSPHERIC CHALLENGES

At 1550 nm, there is a transmission window through the atmosphere. Terrain can be seen through smoke and haze as well as through cirrus clouds (2). However, even with a good window of transmission, propagation of light through the atmosphere is still susceptible to turbulence and other effects. Our studies are showing the effect of "wedging" on beam pointing over the large body of water at CBD Figure 6 shows how the BER is affected over time across the water (14).

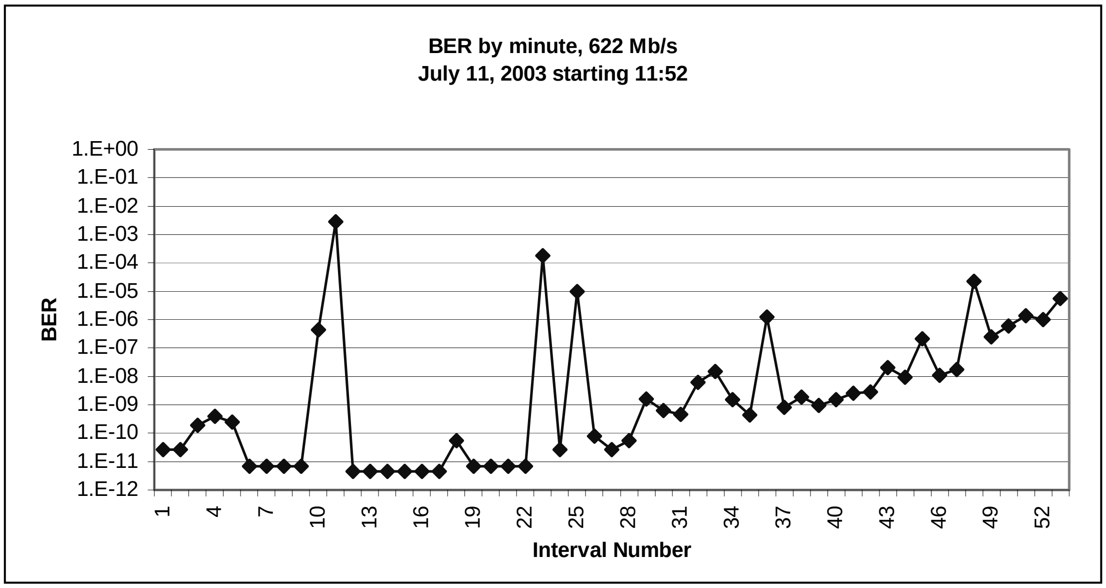


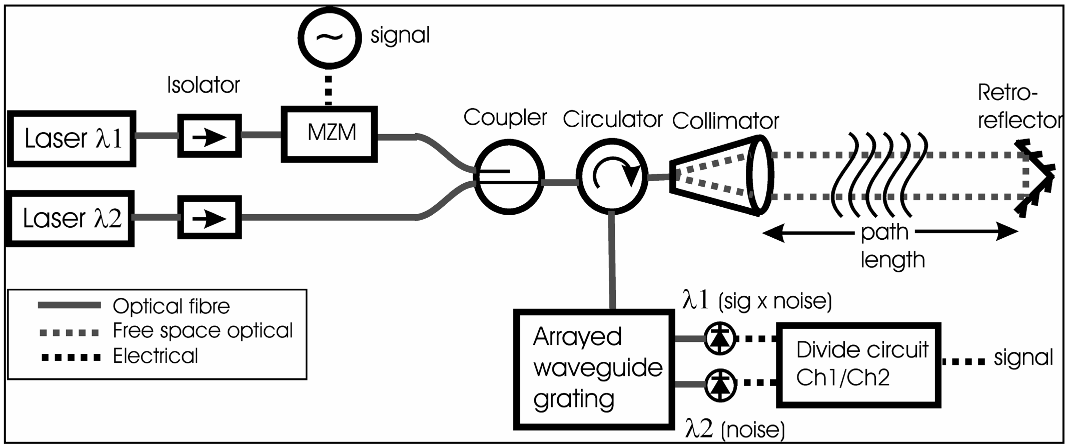
Figure 6. This graph shows how the bit error rate worsens over time for a laser data link where the beam was propagated over 16.2 km of water at the NRL Chesapeake Bay Detachment Laser Communications Test Facility (Ref. 14).

The BER in the figure was calculated in 1-minute intervals spanning an hour beginning at 13:44 at CBD. The pointing of the transmitter was not adjusted while data were taken. The lack of active or even human corrected pointing explains some of the rise in BER toward the end of the hour due to thermal layering (15).

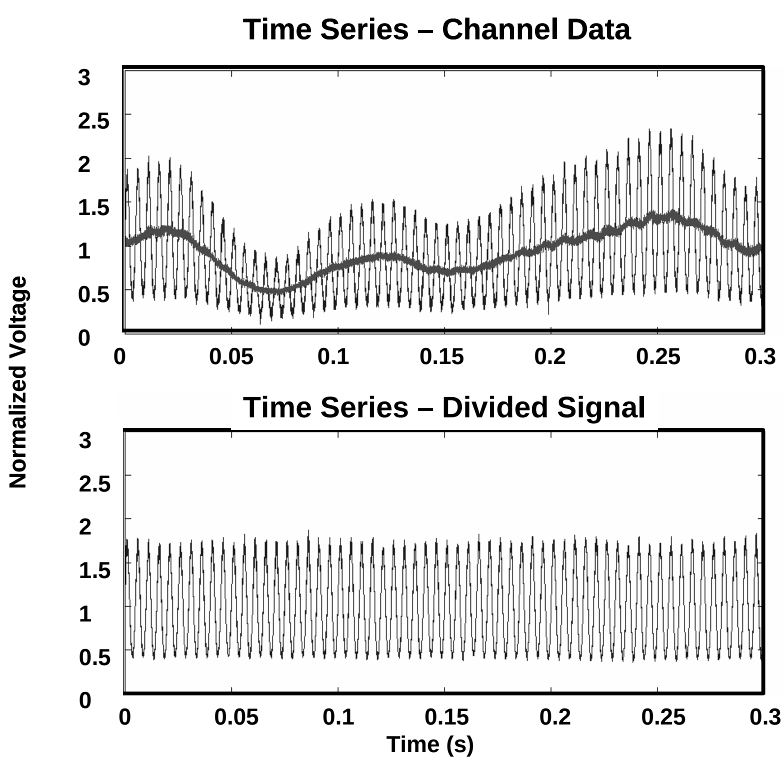
In addition to its effect on pointing, a large body of water can contribute to a unique form of miraging. In this latter phenomena, as the temperature increases throughout the day (thermal layering), objects some distance away distort, and even appear to double in some cases. These effects mean that the beam can be misdirected to the receiver and signal loss can occur. Understanding the phenomena is requisite to developing reliable links across the water, especially for ship-to–shop communications. The use of a fiber positioner combined with a position sensing device (PSD) is among the techniques under study. The technique is proving to be an effective method to mitigate these effects. A description of efforts in this area described elsewhere in these Proceedings (16). It further anticipated that implementation of the lower order Adaptive optics discussed above will contribute to more robust links.

Another technique under experimental investigation at NRL is the use of two frequencies to cancel out the effect of the atmosphere on data transmission. The technique, common mode rejection, was successfully implemented in Australia by Grant, et. al. (17) and is being adapted to the NRL testing environment to compare results at different latitudes and under different environmental conditions. Preliminary results are presented elsewhere in these

Proceedings (18). Figure 7 shows the experimental configuration used in the Cowley experiments. Time series results are also shown from the Cowley experiment with this technique. The method successfully takes out the slowly varying changes in amplitude and enables robust signal recovery. It has real potential for the NRL analog efforts as we migrate toward transmitting undigitized data across long links over water



(a)



(b)

Figure 7. (a) Experimental configuration to reduce the effect of the atmosphere on analog free space data links using common mode rejection (17); and (b) some results. This method is being adapted to the NRL CBD test facilities.

8. CONCLUSIONS

There has been considerable progress made in the extension of resources at the NRL to advance the study of free space infrared and optical communications. . Test facilities have been improved to investigate the effects of the atmosphere on free space communications links over large bodies of water. Context for the studies include ship-to-ship communications as well as other operational scenarios which may involve harvesting data remotely in the littoral region. The development of the MQW MRRs has given rise to other related investigations to lower the power required to support sensor/comms packages. Notably, photovoltaic powered units which might be self-powered in the future are under investigation. In addition, migration to analog modulation from digitations of the signal at the sensor is under consideration due to the promise of considerably reducing the power draw requirements and the amount of bandwidth required to transmit a signal with fidelity. Conversion to analog however, makes the link more susceptible to the atmosphere. Consequently, we have begun to look at ways to both modulate the MRR, and to forward better control beam tracking and pointing through lower order adaptive optics.

REFERENCES

1. H. Hemmati, ET. al., "Comparative Study of Optical and RF Communications System for a Mars Mission Part II. Unified Value Metrics, *Proceedings of the SPIE*, **2699**, pp. 146-164 (1996).

2. G.C. Gilbreath, et. al., "Progress in development of multiple quantum well retromodulators for free-space data links", *Opt.l Eng.*, **42**(6), 1611-1617 (2003).

3. W. S. Rabinovich, et.al, "Free-space Optical Free-Space Communications Link at 1550 nm using Multiple Quantum Well Modulating Retroreflectors in a Marine Environment", *Opt. Eng*., **44(5**), pp. 056001-056012 (2005).

4. http://mrr.nrl.navy.mil

5. Mark. L. Bierman, et. al., "Design and analysis of a diffraction limited cat's eye retroreflector", *Opt. Eng.*, **41**(7), pp. 1655-1660 (2002).

6. William S. Rabinovich, et. al., "Performance of cat's eye modulating retro-reflectors for free-space optical communications", *Proceedings of the SPIE*, **5550**, pp. 104-114 (2004).

7. J. L. Murphy, et. al, " FM-MRR Analog Audio System", *Proceedings of the SPIE*, **5892-72** (2005).

8. Robert Walters, et. al., "Photovoltaically Powered Modulating Retroreflectors", *Opt. Eng.*, Accepted for Publication (July, 2005).

9. Sergio R. Restaino, et. al., "Analysis of the Naval Observatory Flagstaff Station 1-m telescope using annular Zernike polynomials", *Opt. Eng.*, **42**, pp. 2491-2495 (2003).

10. Christopher C. Wilcox, et. al., "Mounting a deformable mirror onto a controllable tip/tilt platform", *Proceedings of the SPIE*, **5717**, pp. 36-42 (2005).

11. Jonathan R. Andrews, et. al., "Optical Testbed for Comparative Analysis of Wavefront Sensors", *Proceedings of the SPIE*, **5892** (2005).

12. Christopher I. Moore, et. al., "Spatial intensity correlation and aperture averaging measruemnts in a 20 mile retroreflected lasercom link", *Proceedings of the SPIE*, **5169**, pp. 474-482 (2004).

13. Christopher I. Moore, et. al., "Overview of NRL's maritime laser communication test facility", *Proceedings of the SPIE*, **5892-06** (2005).

14. M.J. Vilcheck, et. al. , "Progress in high-speed communication at the NRL Chesapeake Bay Lasercom Facility", *Proceedings of the SPIE*, **5160**, pp. 466-473 (2003).

15. William P. Hooper, et. al., “Retrieval of near-surface temperature profiles from passive and active optical measurements”, *Opt. Eng.* **41**, 1586-1602 (2002).

16. M. R. Suite, et. al., “Steering compensation for strong vertical refraction gradients in a long distance free space optical communication link over water”, *Proceedings of the SPIE*, **5892-67** (2005).

17. K. J. Grant, et. al., “Mitigation of Scintillation Noise by Common Mode Rejection”, *Proceedings of the SPIE*, **5793**, pp. 106-117 (2005).

18. K. J. Grant, et. al., “Mitigation of scintillation noise in a 32-km maritime path”, *Proceedings of the SPIE*, **5892-68** (2005).